ADVECTION–DOMINATED INFLOW/OUTFLOWS FROM EVAPORATING ACCRETION DISKS

R. Turolla
Department of Physics, University of Padova,
Via Marzolo 8, I–35131 Padova, Italy
e–mail: turolla@pd.infn.it

AND

C.P. Dullemond
Max Planck Institut für Astrophysik,
Karl Schwarzschild Strasse 1, D–85748 Garching, Germany
e–mail: dullemon@mpa-garching.mpg.de

Draft version February 22, 2000

ABSTRACT

In this *Letter* we investigate the properties of advection–dominated accretion flows (ADAFs) fed by the evaporation of a Shakura–Sunyaev accretion disk (SSD). In our picture the ADAF fills the central cavity evacuated by the SSD and extends beyond the transition radius into a coronal region. We find that, because of global angular momentum conservation, a significant fraction of the hot gas flows away from the black hole forming a transsonic wind, unless the injection rate depends only weakly on radius (if $r^2\dot{\sigma} \propto r^{-\xi}$, $\xi < 1/2$). The Bernoulli number of the inflowing gas is negative if the transition radius is $\lesssim 100$ Schwarzschild radii, so matter falling into the hole is gravitationally bound. The ratio of inflowing to outflowing mass is $\approx 1/2$, so in these solutions the accretion rate is of the same order as in standard ADAFs and much larger than in advection–dominated inflow/outflow models (ADIOS). The possible relevance of evaporation–fed solutions to accretion flows in black hole X–ray binaries is briefly discussed.

Subject headings: accretion, accretion disks — black hole physics — hydrodynamics

1. INTRODUCTION

In recent years X–ray and optical observations provided increasing evidence that advection–dominated flows (ADAFs, Ichimaru 1977; Narayan & Yi 1995b; Abramowicz et al. 1995) are a ubiquitous feature of accretion at all scales, from black holes (and possibly neutron stars) in X–ray binaries (e.g. Narayan 1996; Esin, McClintock & Narayan 1997; Menou et al. 1999) to supermassive black holes in the center of galaxies (e.g. Narayan, Yi, & Mahadevan 1995, Lasota et al. 1996, Narayan et al. 1999; Gammie, Narayan, & Blandford 1999).

Despite their structure being inherently two–dimensional, much theoretical work on ADAFs still relies on a vertically–integrated approach, which, although questionable, may indeed catch some of the essential properties of the model, as its successful application to various sources shows. The standard ADAF picture was, however, challenged in a recent paper by Blandford, & Begelman (1999). Since, at least in self–similar ADAFs, the Bernoulli number is positive (as already noted by Narayan, & Yi 1994, 1995a), they suggested that a large outflow may form. If this is the case, they have shown that the mass carried out by the wind must exceed by orders of magnitude that which is crossing the horizon, turning ADAFs into Advection–Dominated Inflow/Outflow Solutions, or ADIOS. Although the positiveness of the Bernoulli number is only a necessary (but not sufficient) condition for starting an outflow, this argument poses a serious problem to the ADAF model for black hole accretion and must be addressed carefully.

Goal of this *Letter* is to investigate how, and to which extent, the inclusion of the source of ADAF material affects the Bernoulli number and the onset of a wind. Advection–dominated flows in black hole X–ray binaries (BHXBs) are most likely produced by the evaporation of a Shakura–Sunyaev disk (SSD, Shakura, & Sunyaev 1973), as observational and theoretical arguments suggest (e.g. Narayan, Mahadevan, & Quataert 1999). The evaporation process is not fully understood as yet (see e.g. Meyer, & Meyer–Hofmeister 1994; Honma 1996; Dullemond 1999; Różańska 1999) and definitely needs to be modeled in at least two spatial dimensions. Here we just assume a simple, analytical law for the evaporation rate and limit ourselves to a vertically–integrated description of the hot flow. A quite general argument, based on angular momentum conservation, indicates that purely inflowing solutions can not exist if the accretion rate decreases with radius. Numerical models, computed for several values of the α–viscosity parameter and of the transition radius R_0, support this conclusion. In all of them a stagnation radius (where the radial velocity vanishes) separates an inner inflowing region from an outer transsonic wind. We find that the Bernoulli number for the infalling gas is negative if the transition radius is less than ~ 100 Schwarzschild radii. In these solutions about 1/3 of the mass carried inwards from large radii by the thin disk reaches the horizon. More extended inflows, with $R_0 \gtrsim 100 R_s$, have a region of positive Bernoulli number, and are likely to be replaced by an ADIOS.

2. THE MODEL

We consider a highly idealized model for a hybrid accretion flow, in which a hot, advection–dominated phase coexists with a Shakura–Sunyaev disk. All the ADAF gas is assumed to be supplied by the evaporation of the surface layers of the SSD which extends down to the transition radius R_0. In the following we will not be concerned with the SSD anymore and focus our attention on the hot component. The inner rim is chosen to be at $R_{in} = 3GM/c^2$ (M is the hole mass), and $R_0 > R_{in}$. The advection–dominated flow is described by the usual stationary, vertically–integrated equations (see e.g. Narayan, Kato, & Honma 1997), which now include the energy and momentum exchange between the hot gas and the evaporating material; the standard α–prescription for viscosity is retained, the pseudo–Newtonian potential is used to describe the gravitational field and we neglect radiative losses. The physics of the evaporation process is still unclear, so we just assume that matter is lost from the SSD (per unit area and time) according to the simple law

$$\dot\sigma(R) = \begin{cases} \dot\sigma_0\,(R/R_0)^{-\xi-2} & R \geq R_0 \\ 0 & R < R_0\,. \end{cases} \tag{1}$$

The continuity equation reads

$$\frac{d(R\Sigma v_R)}{dR} = R\dot\sigma \tag{2}$$

which can be immediately integrated to yield $-2\pi R\Sigma v_R = \dot M_{ADAF}(R)$. In the previous expressions Σ is the surface density and v_R the radial velocity, chosen to be negative for matter flowing towards the hole. The ADAF accretion rate now depends on R and is given by

$$\dot M_{ADAF}(R) = \begin{cases} \dot M\,(R/R_0)^{-\xi} - \dot M_{out} & R \geq R_0 \\ \dot M - \dot M_{out} & R < R_0 \end{cases} \tag{3}$$

where $\dot M_{out} = (2\pi\ R\Sigma v_R)|_{R\to\infty}$, $\dot M = 2\pi\xi^{-1}\dot\sigma_0 R_0^2 = \dot M_{SSD}(R\to\infty)$ is total accretion rate, and we consider only the case $\xi > 0$, so $\dot M_{ADAF}$ decreases with R. If $\dot M_{out} > 0$, $\dot M_{ADAF}$ becomes negative for $R > R_{st} = [1 + (\dot M - \dot M_{out})/\dot M_{out}]^{1/\xi} R_0$ and the gas crosses the horizon at a rate $\dot M_{in} = \dot M - \dot M_{out} < \dot M$; this implies that also v_R has to switch sign at the stagnation radius R_{st}.

In the following we assume that the injected material rotates at the Keplerian angular speed Ω_K and that the rising gas elements move predominantly in the vertical direction with velocity $\ll \Omega_K R$. Since the ADAF is expected to rotate at $\Omega < \Omega_K$, the difference in the circular speeds produces a torque. Conservation of angular momentum then implies

$$\Sigma R v_R \frac{d(R^2\Omega)}{dR} - \frac{d}{dR}\left(\Sigma\nu R^3 \frac{d\Omega}{dR}\right) = \dot\sigma(\Omega_K - \Omega)R^3 \tag{4}$$

where $\nu = 2/3\alpha c_s H$ is the viscosity coefficient, H the flow half–thickness and c_s the isothermal sound speed. Other possible sources of friction between the SSD and the ADAF like, e.g., magnetic stresses, have been neglected.

The ADAF has to spend part of its energy to heat up the injected gas which has initially the same temperature of the Shakura–Sunyaev disk. At the same time heat is produced by frictional dissipation. Including both these effects, the local energy balance takes the form

$$v_R\left[(\gamma-1)\frac{dc_s^2}{dR} - c_s^2\frac{d\ln(\Sigma/H)}{dR}\right] - \nu\left(R\frac{d\Omega}{dR}\right)^2 = \frac{\dot\sigma}{\Sigma}\left[\frac{1}{2}v_R^2 + \frac{1}{2}R^2(\Omega_K-\Omega)^2 - \frac{\gamma}{\gamma-1}c_s^2\right] \tag{5}$$

where γ is the adiabatic index and we assumed that the rising gas elements do not suffer any energy loss before thermalizing with the hot plasma.

Finally, the radial force balance is expressed as

$$v_R\frac{dv_R}{dR} + (\Omega_K^2 - \Omega^2)R + \frac{dc_s^2}{dR} + c_s^2\frac{d\ln(\Sigma/H)}{dR} = -\frac{\dot\sigma}{\Sigma}v_R\,; \tag{6}$$

the last term arises because the injected mass has zero radial momentum and is usually negligible. As expected, Eqs. (2), (4)–(6) reduce to the standard ADAF form for $\dot\sigma = 0$.

3. GLOBAL SOLUTIONS FOR THE HOT FLOW

It can be easily shown that, under the usual assumptions, the flow equations admit a self–similar solution. However, at variance with standard advection–dominated models, a self–similar regime is not always allowed for evaporation–fed ADAFs. In fact, at least if $0 < \Omega < \Omega_K$, angular momentum conservation implies $(1-2\xi)/v_R < 0$, so inflowing self–similar solutions are ruled out unless $\xi < 1/2$. The reason for this is as follows. If the amount of mass injected into the ADAF drops off too quickly with increasing R, viscous stresses can not transport enough angular momentum outwards because the density becomes too low at large radii. The ADAF can not get rid of its angular momentum by transferring it to the SSD either, since the cold disk rotates faster. On a physical basis, it seems therefore unlikely that purely inflowing global solutions could exist. The only possibility for the flow to transport efficiently angular momentum to infinity is to advect it, reversing its motion from a certain radius onwards.

Eqs. (2), (4)–(6) have been solved numerically using a Henyey relaxation method (Dullemond, & Turolla 1998). Despite several attempts, no purely inflowing solution was found for $\xi > 1/2$, as the previous argument predicts. In all models both the outflow and the inflow are transsonic. The presence of three critical points (the two sonic radii and the stagnation radius) reduces the number of the boundary condition from five (there are three first order and one second order differential equations) to two, the other three being replaced by regularity conditions at the critical points. Since the viscosity must be well–behaved at both the inner and outer edge (the no–torque condition, see Narayan, Kato, & Honma 1997), we require

$$\frac{d\log\Omega}{d\log R} = -2 \qquad \text{at } R = R_{in} \text{ and } R = R_{out}\,. \tag{7}$$

This choice introduces no further degree of freedom. The solution depends only on the function $\dot\sigma(R)$, on α and γ. Both the mass loss rate at large radii $\dot M_{out}$, and the stagnation radius follow from the calculation and are found to obey the analytical expression for R_{st} derived in §2 to high accuracy.

We have computed several series of models with $0.1 < \alpha < 1$, $1/2 < \xi < 3/2$ and $\gamma = 3/2$, varying R_0 in the range $20R_s$–$1000R_s$. As Eqs. (4)–(6) show, v_R, Ω and c_s are independent of $\dot\sigma_0$ and M; the same is for the ratio $\dot M_{in}/\dot M_{out}$ of accretion to mass loss rates. The radial dependence of v_R and c_s for a typical run is plotted in Fig. 1; solutions with different values of α and ξ show the same general behaviour. Only a limited ξ–range was considered here, but we have verified that steeper (e.g. exponential) injection laws give quite similar results. The accretion to mass loss ratio goes from $\dot M_{in}/\dot M_{out} \sim 0.5$ to ~ 0.3 as R_0 increases from 20 to 500 R_s and is not much dependent of α and ξ. Correspondingly, R_{st} is in all cases about $1.5R_0$. As expected, for $R_0 \gtrsim 500R_s$ the inflow closely resembles standard ADAFs and, in particular, has a nearly self–similar region at intermediate radii. For smaller values of R_0 the accretion flow has no room to attain self–similarity, being squeezed in between the sonic and the stagnation radius.

4. DISCUSSION

Our solutions share with ADIOS the property that a significant (although very different) fraction of the material is expelled in a wind. The two models, however, differ substantially in many respects.

Blandford, & Begelman (1999) constructed self–similar advection–dominated solutions for which the Bernoulli number Be is negative assuming that $\dot M_{ADAF} \propto R^p$ with $p > 0$. They concluded that all the mass which does not reach the horizon escapes in a wind more massive than the ADAF by orders of magnitude. Although no detailed model including the wind has been presented as yet, preliminary hydrodynamical calculations seem indeed to support the original suggestion that the mass inflow rate increases with radius (Stone, Pringle, & Begelman 1999). In addition, 2–D simulations by Igumenshchev, & Abramowicz (1999) have shown that ADIOS–like solutions are present for large α. In our model the outflow is a direct consequence of having assumed that the ADAF material is supplied by the SSD. The accreting gas has to transfer angular momentum to larger radii and, since $\dot M_{ADAF}$ is decreasing with increasing R in the evaporation region, this can not be done by viscous stresses alone. From the stagnation radius onwards, the gas is centrifugally accelerated away from the hole, carrying angular momentum with it: no stationary solution would be possible without an outflowing region. This is not related to the positiveness of the Bernoulli number. Moreover, the wind is not produced by the ADAF itself but originates directly from the evaporating SSD material.

The basic objection Blandford and Begelman raised to standard ADAFs is very general and concerns also the inflowing part of evaporation–fed models. The Bernoulli number for our solutions is shown in Fig. 2. In the wind region the Bernoulli number becomes positive shortly beyond the stagnation radius, while Be can be either positive or negative for the infalling gas, depending on R_0. Solutions with a small transition radius have always $Be < 0$. This can be understood considering the energy the hot flow transfers to the cold injected material (last term in eq. [5]). The evaporation stops at R_0 but the inflowing gas will stay cooler (with respect to a standard ADAF) a bit further down. For $R_0 \lesssim 100R_s$ viscous dissipation has no time to heat the flow sufficiently before it crosses the horizon, keeping Be negative (see also Nakamura 1998 for a discussion on the sign of the Bernoulli number in non–self–similar ADAF solutions). As R_0 increases above $\sim 100R_s$ the Bernoulli number is still negative close to R_0 but it flips sign as soon as the inflowing gas has become hot enough. An ADIOS–type wind may be expected where $Be > 0$.

The inclusion of a source for the hot gas points towards the existence of a more general class of advection–dominated flows, with somewhat intermediate characteristics between standard ADAFs and ADIOS. In the light of the relation to (and possible inclusion of) ADIOS–type flows, we refer to these models as "Consistent Inflow And Outflows", or CIAOs.

Our vertically–integrated CIAO model has to be supported by detailed 2–D and 3–D hydrodynamical calculations, but the present analysis suggests that for $R_0 \lesssim 100R_s$ the inflowing matter is gravitationally bound and no ADIOS–like wind is expected to be present. CIAOs can supply the central hole with about 1/3 to 1/4 of the mass originally carried inwards by the thin disk. This may be relevant for applications of advection–dominated flows to BHXBs and AGNs. It has been often proposed (e.g. Narayan 1996; Esin, McClintock, & Narayan 1997; Belloni, et al. 1997; Narayan, Mahadevan & Quataert 1999) that the different spectral states observed in BHXBs may be explained in terms of a bimodal disk in which the transition radius varies with time. The inferred values of R_0 are in between few R_s and $\approx 100\,R_s$. Recent optical/UV observations also indicate that the inner edge of the thin disk in the nucleus of M81 and NGC 4579 lies at $\sim 100\,R_s$ (Quataert, et al. 1999). Although a more detailed analysis is definitely required before any firm conclusion can be drawn, it is interesting to note that the maximum value of the transition radius for which our models have $Be < 0$ is close to the observed limit mentioned above. CIAOs may comfortably provide the hot accretion flow in all the range of R_0 implied by observations. At the same time, the absence of hot flows with an extent $\gtrsim 100R_s$ can be interpreted in terms of the onset of a strong wind which, as in ADIOS, blows off the accreting part of the CIAO and reduces dramatically the accretion rate onto the black hole.

REFERENCES

Abramowicz, M. A., et al. 1995, ApJ, 438, L37
Belloni, T., et al. 1997, ApJ, 479, L145
Blandford, R.D., & Begelman M.C. 1999, MNRAS, 303, L1
Dullemond, C. P. 1999, A&A, 341, 936
Dullemond, C. P., & Turolla, R. 1998, ApJ, 503, 361
Esin, A. A., McClintock, J. E., & Narayan, R. 1997, ApJ, 489, 865
Gammie, C.F., Narayan, R., & Blandford, R.D. 1999, ApJ, 516, 177
Honma, R. 1996, PASJ, 48, 77
Ichimaru, S. 1977, ApJ, 214, 840
Igumeshchev, I., & Abramowicz, M.A. 1999, MNRAS, 303, 309
Lasota, J.P., et al. 1996, 462, 142
Menou, K., et al. 1999, ApJ, 520, 276
Meyer, F., & Meyer-Hofmeister, E. 1994, A&A, 288, 175
Nakamura, K.E. 1998, PASJ, 50, L11
Narayan, R., & Yi, I. 1994, ApJ, 428, L13
Narayan, R. 1996, ApJ, 462, 136
Narayan, R., Yi, I., & Mahadevan, R. 1995, Nature, 374, 623
Narayan, R., & Yi, I. 1995a, ApJ, 444, 231
Narayan, R., & Yi, I. 1995b, ApJ, 452, 710
Narayan, R., Kato, S., & Honma, F. 1997, ApJ, 476, 49
Narayan, R., et al. 1998, ApJ, 492, 554
Narayan, R., Mahadevan, R., & Quataert, E. 1999, in The Theory of Black Hole Accretion Disks, Abramowicz, M.A., Bjornsson, G. and Pringle, J.E. eds. (Cambridge: Cambridge University Press)
Quataert, E., et al. 1999, ApJ, 525, L89
Różańska, A. 1999, MNRAS, 308, 751
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Stone, J.M., Pringle, J.E., & Begelman, M.C. 1999, ApJ, submitted (astro–ph/9908185)

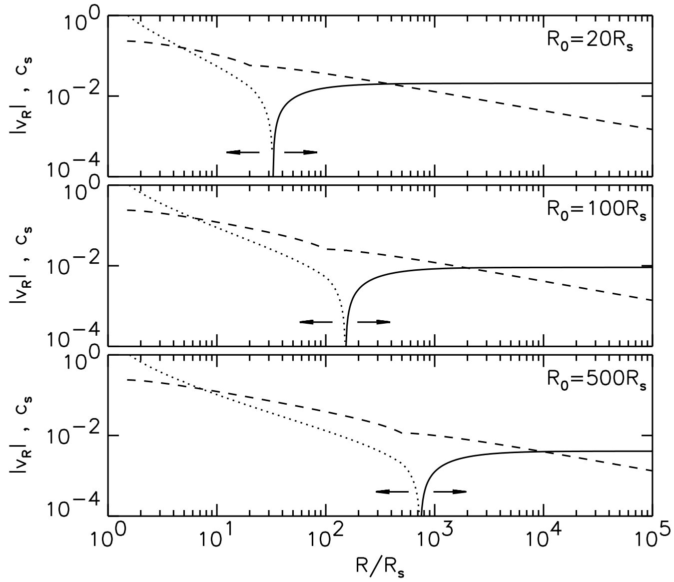

FIG. 1.— The radial run of $|v_R|$ (dotted/full line for negative/positive values) and c_s (dashed line), both in units of c, for $\alpha = 0.5$, $\xi = 0.75$ and three values of R_0. From top to bottom $\dot{M}_{in}/\dot{M}_{out} = 0.44$, 0.37 and 0.35. The arrows mark the radial flow direction.

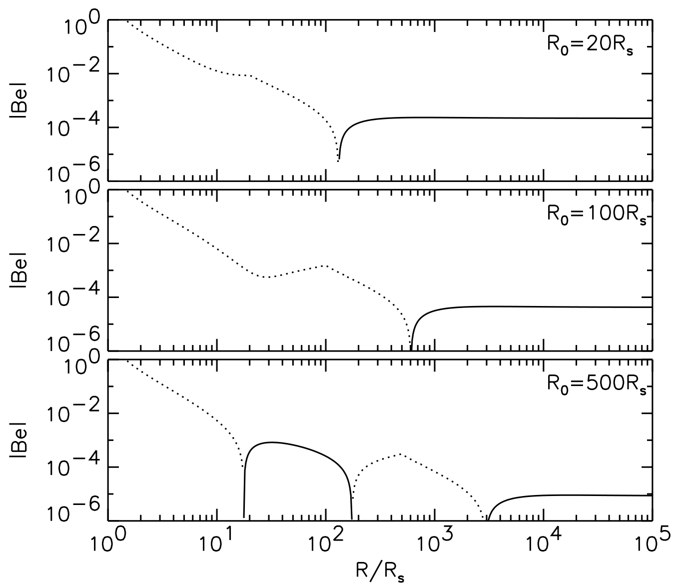

FIG. 2.— Same as in fig. 1 for $|Be|$ (in units of c^2). Be is negative for $R < R_{st}$ in the middle panel, but the dip at $\sim 20R_s$ signals that it is going soon to switch sign in the inflowing region.